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Transmission of light trough [i.e. through] erbium doped TeO2 fibers

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TRANSMISSION OF LIGHT TROUGH ERBIUM DOPED TeO2 FIBERS

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Transmission of Light Trough Erbium Doped TeO_2 Fibers

by

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The greatest gratitude I owe to my parents, Nikosava and Slobodan, and this thesis I dedicate to them.

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Abstract

We measured the transmission of light through erbium doped TeO_2 fibers under a pumping of 980 nm light. The tellurite glasses doped with erbium are interesting because of broad emission spectra. Our measurements show up to 190 nm broad erbium spontaneous emission (ESE). Also, we have looked at low signal gain of 1550 nm laser, as well as at upconversion pumping processes.

Transmission of Light Trough Erbium Doped TeO_2 Fibers

Introduction

The family of tellurite glasses is potential candidate to be exploited in optical applications because they have very high indices of refraction, large nonlinear refractive indices, and relatively low phonon energy spectra. The high nonlinear refractive index and the low energy spectra make tellurite glass fibers and integrated optics uniquely suited for special nonlinear and laser applications. For example, the lower phonon energy results an a lower nonradiative transition rate between adjacent rare earth energy levels, thereby leading to fluorescence and laser emission from additional energy levels that are not possible for silicate glasses.

The tellurite glasses doped with erbium are interesting because of broad emission spectra. The main aim of these fibers is to have one with the smallest possible core, but with the broadest emission spectra, which means broadest bandwidth available for more channels. Recently, erbium doped glasses have received a great deal of attention as fiber amplifiers. Fiber gains in excess of 5dB/mW with total gains greater than 35 dB have been achieved.

Figure 1 shows schematic diagram of the third-generation fiber amplifier with laser diode pumping configuration. The concept of the optical fiber amplifiers is based on amplification of an optical signal in a fiber by using the stimulated emission of optically excited rare-earth ions in the fiber core. The operational principle of fiber amplifiers is the same of that of lasers, except that amplifiers do not need a cavity whereas lasers need one for oscillation. As a result of a high numerical aperture and single-mode operation, these fibers have a strongly waveguiding structure.

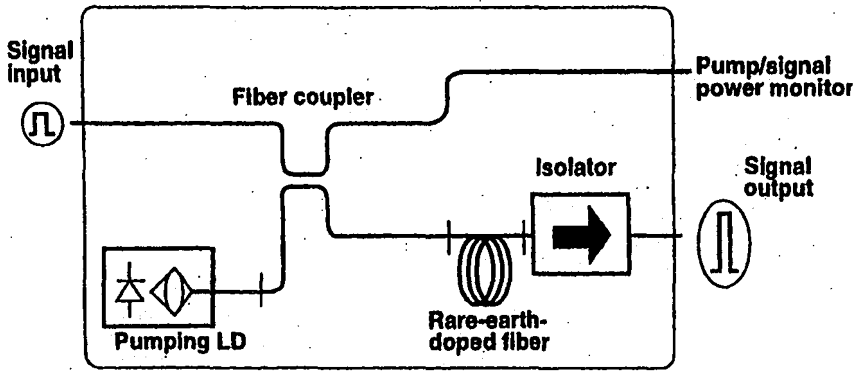

Figure 1 Schematic diagram of the third-generation fiber amplifier with a laser diode pumping configuration [1].

Figure 2 shows the basic configuration and the principle of optical signal amplification in rare-earth-doped fibers. In order to achieve efficient amplification in this kind of fibers, rare-earth ions should be able to operate in a radiative transition with high quantum efficiency. This should have no quenching effects of ions, a low moderate transition caused by multiphonon relaxation, and a high optical intensity in the core part. Additional requirement is need for efficient pumping. Also, the fiber host should exhibit low loss, including low scattering loss and low absorption loss, preferably have a low phonon energy for a low nonradiative transition.

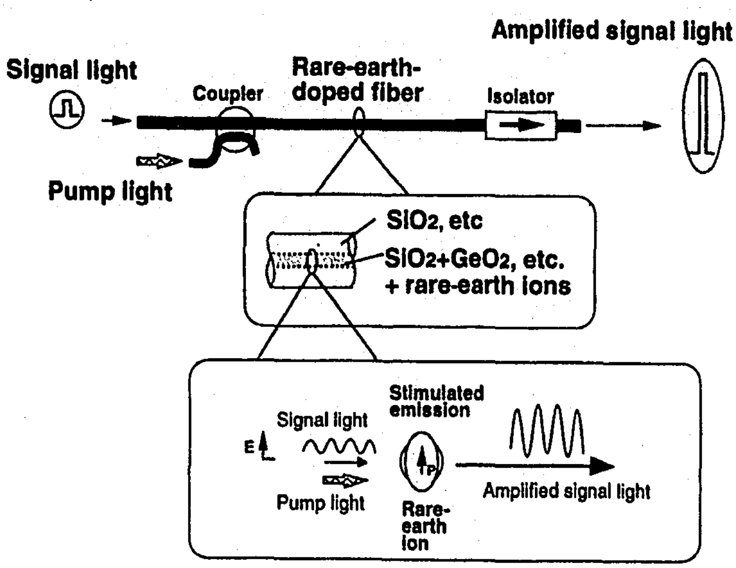

Figure 2 Basic configuration and principle of optical signal amplification in rare-earth-doped fibers [1].

Characteristics of erbium ions for 1.5-μm amplification are shown on figure 3. Erbium ions are pumped at 980 nm and 1480 nm. The signal is amplified by the transition from $^4I_{13/2}$ to $^4I_{15/2}$. This is three-level transition, and its quantum efficiency is very high. But, there are two major degradation processes that affect amplification: the pump excited-state absorption (ESA) with 980 nm pumping [2-4], and cooperative upconversion with 1.48-μm pumping [5,6]. It is important to emphasize that 980-pump ESA appears during high-power operation, and cooperative upconversion appears when the erbium ion concentration is high.

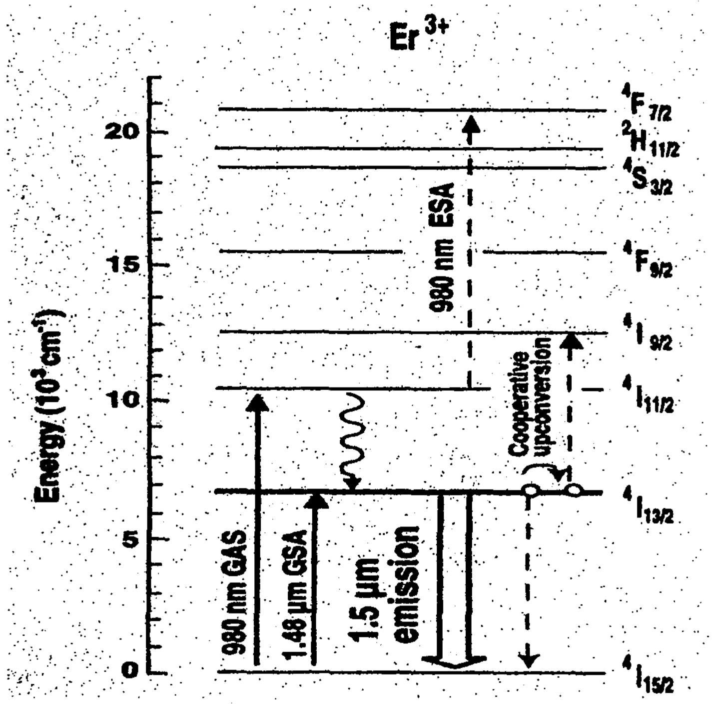

Figure 3 Characteristics of erbium ion [2-9].

Erbium doped tellurite glasses have shown excellent potential for optical applications, because of the reasons mentioned above. The main objectives of this thesis are to research the transmission of light through erbium doped TeO_2 fibers under 980 nm pumping, to measure the transmission spectra and compare it with similar spectra in other glasses, and to find the dependence of gain on pump and signal input power, and pump and signal optical mode in the fiber.

Experiment

The experimental setup is shown on the Figure 4. We have used a 980 nm laser to pump the Er doped tellurite fiber. The pump light enters 980 nm/1550 nm Wavelength Division Multiplexer (WDM). The WDM output fiber had a 10 μm core diameter. From the sample, we are leading signal to the Optical Spectrum Analyzer.

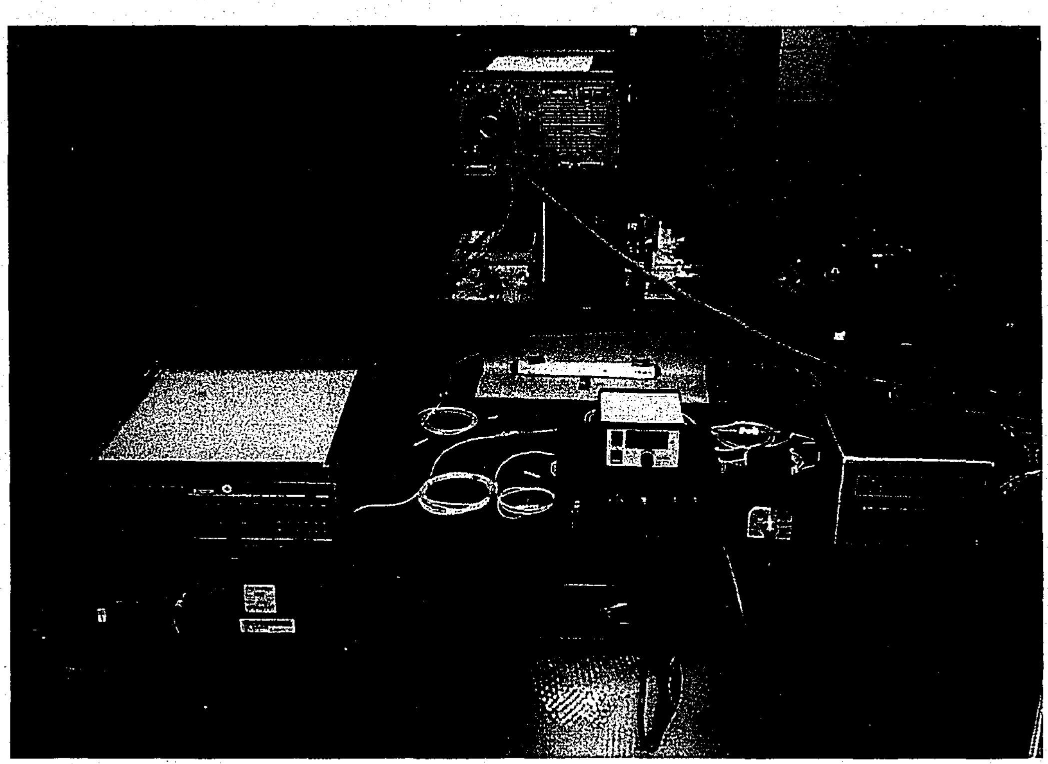

Figure 4 Experimental setup.

The most sensitive part of the experiment is splicing the silica and telluride fibers. Tellurite fibers are very fragile, so we cannot use standard tools, such as cleavers and strippers, to splice them. Since we had to use capillary tubes like a protector for TiO_2 fiber, and to glue and polish its ends, the first idea was to align WDM output fiber with the Er doped telluride fiber, and also to couple the other end of the sample to another silica based fiber attached to optical spectra analyzer. For the experimental setup, we used standard micropositioners and standard

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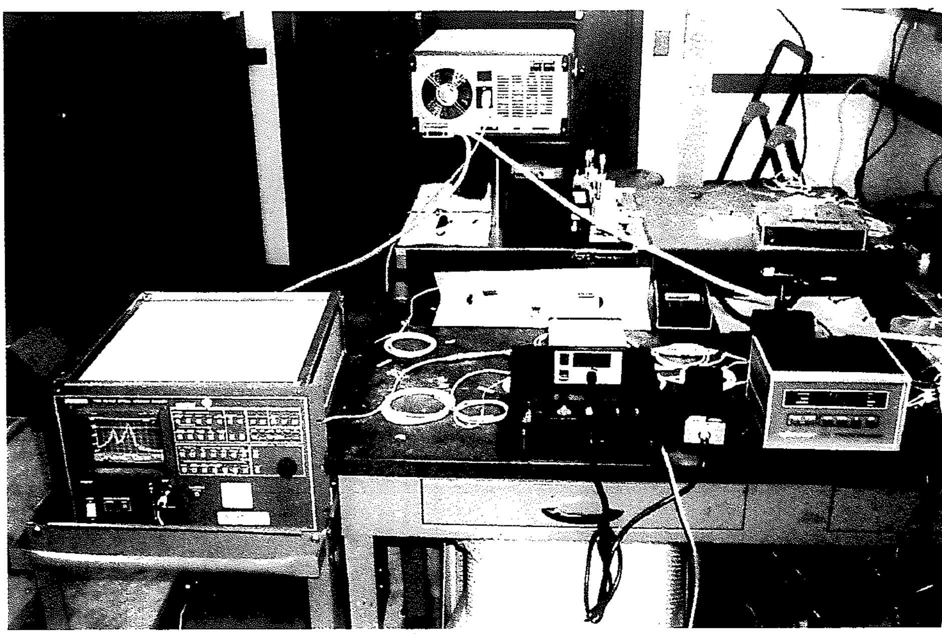

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The reasons for that were several. There was too much free space for this setup, so the loss of the input signal was huge. Because of the 0.936 mm of the inner diameter of the capillary tube, the fiber with only 0.44 mm of average outer diameter could be anywhere, as well as the core of the fiber inside the plastic of the fiber. Further, the core of the sample fiber was only 3 μm, which we should align with the silica fiber with 10 μm core. Also, using objectives to focus the laser beam would weaken the signal. Finally, we were doing alignment only by naked eye, which is not very precise.

Our next attempt was to mechanically splice silica fiber with the Er doped telluride fiber. The idea was similar to the first one: to put fiber inside the capillary tube, to fix that with epoxy, and after that to polish the ends. We made a sample with 44.7 μL capillary tube, which has inner diameter of 0.936 mm and an outer diameter of 1.372 mm. Also, we needed a holder for that sample, which we hold during the polishing process. The holder is in shape of cylinder with the hole for capillary tube along the vertical axes of cylinder. Process of making a holder is also sensitive, because of the drilling of such small holes like we need - less that 1.4 mm. We were limited with the length of cylinder, because the maximum possible depth of the drill was around 2.5 cm. So, we drilled from both sides, and achieved a 5 cm long cylinder.

The polishing process is the most important and sophisticated part of preparing the samples, because of very fragile fibers. For the beginning, we used 12 μm polishing paper, than 8 μm paper, 5 μm, and 1μm polishing paper. For finishing, we used 0.3 μm polishing paper. We prepared several samples with different length: 7.5 cm, 10 cm, and 12,5 cm. It is very important to have very good polished ends, as good as we can make, because the final loss of the signal depends on how good flat surface of the fiber we have. The quality of the surface is proportional with the time we were able to spend for polishing.

With Dr. Refik Kortan from Lucent Technologies, using equipment in his lab, we were able to see and confirm that we can guide the light through the tellurite fiber. We put light from 630 nm laser trough the samples. The light from the sample we collected with CCD camera, and we were able to see that light on the screen of the monitor.

We saw under the microscope with magnification of 5x, 20x, 50x, and 150x objectives, the cross-section of the sample we made first, as well as the cross-sections of some other fibers, which we wanted to use. The equipment we used at Lucent Technologies was consisted of several microscopes and cameras, so alignment was much easier to do. Also, we were able to make pictures of these cross-sections, which we can see on Figure 5.

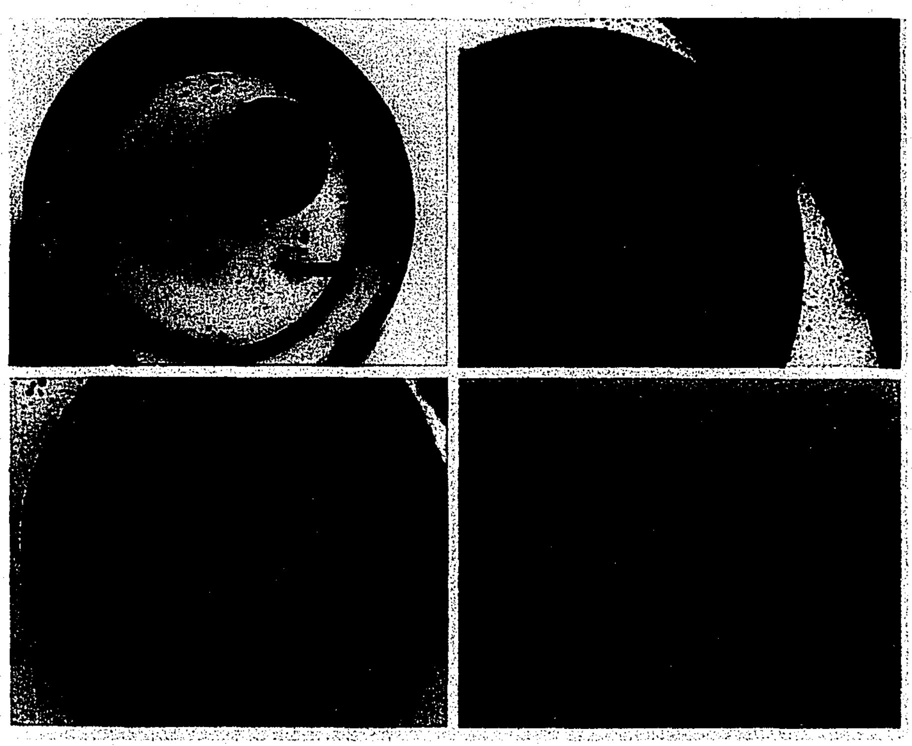

Figure 5 The cross-section of the sample with capillary tube and Er doped tellurite fiber inside.

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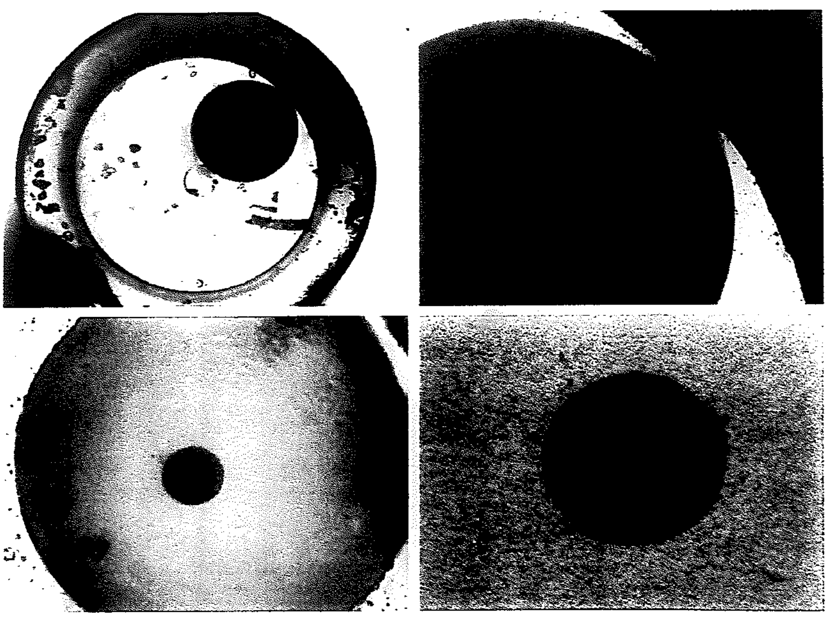


Figure 5 The cross-section of the sample with capillary tube and Er doped tellurite fiber inside.

In Figure 5, we can see the cross-section of the sample with capillary tube and Er doped tellurite fiber inside. Magnification for the left upper picture is 5x, for the right upper picture is 20x, for the left lower picture is 50x, and for the right lower picture is 150x. The core of the presented fiber, as we can barely see on the right lower figure, is approximately 3 μm.

Further, we also used Er doped tellurite fiber with the core diameter of 10 μm. Even with the unpolished ends of that sample, which was approximately 4" long, we were able to easily guide the light from 630 nm laser through the core of that fiber. We repeated the procedure with the 103 cm long tellurite fiber and the result was the same: we guided the light from the same source through the core of the fiber. At the same time, no light was emitted through the other parts of the fiber.

The most sensitive part of this project is certainly the mechanical splicing, as shown in figure 6. Standard two-component epoxy like one that we used here, usually need some time to harden, and during that period previously aligned erbium doped telluride and silica fibers could move. Because off everything mentioned, typical time needed to make one good sample was a couple of days.

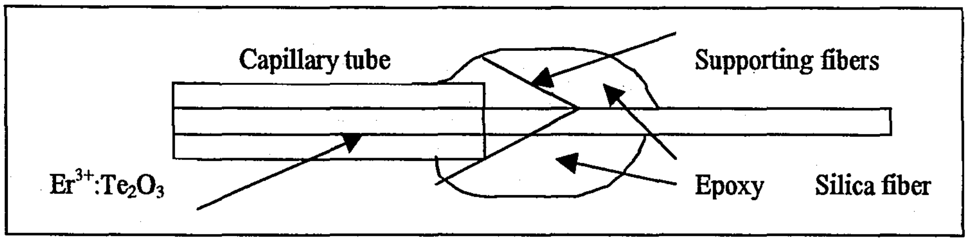


Figure 6 Mechanical splice.

Results

We measured transmission spectra of light through erbium doped TeO_2 fibers pumped with 980 nm. The maximum output power of the 980 nm laser we used here was 180 mW. It is standard 980 nm single mode pump laser. Also, we were using commercial Corning type 10 µm core silica fibers. The loss through the WDM coupler was approximately 40%. Fusion splices had only 0.01 - 0.02 dB of loss. So, the maximum input power of the 980 nm light, which we could put through the sample, was 120 mW.

Concentration of erbium in doped telluride fibers was 4000 ppm. The core was 10 µm, and the cladding was 40 µm. Numerical Aperture of these fibers was ~0.2.

The schematic of the experimental setup is shown in the Figure 7.

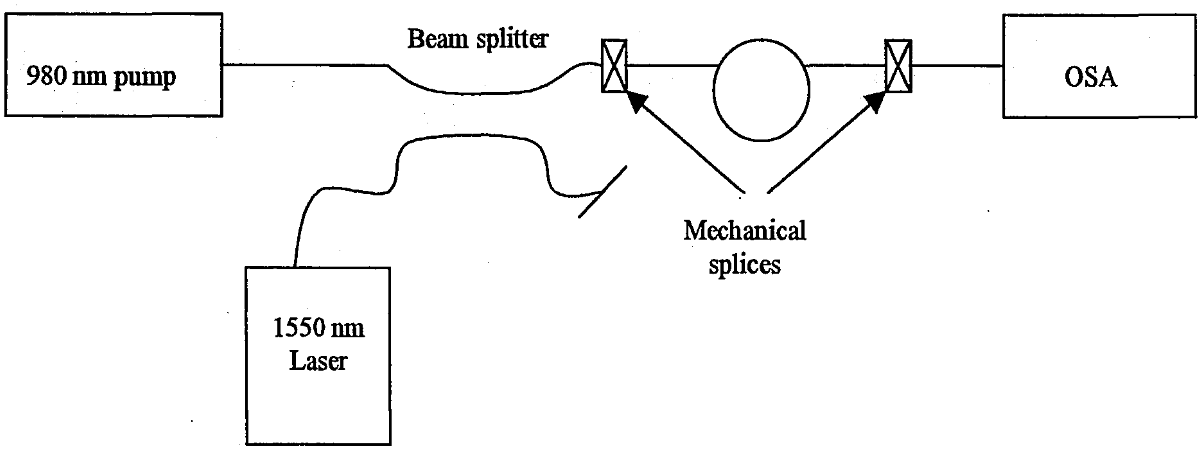


Figure 7 The schematic figure of experimental setup.

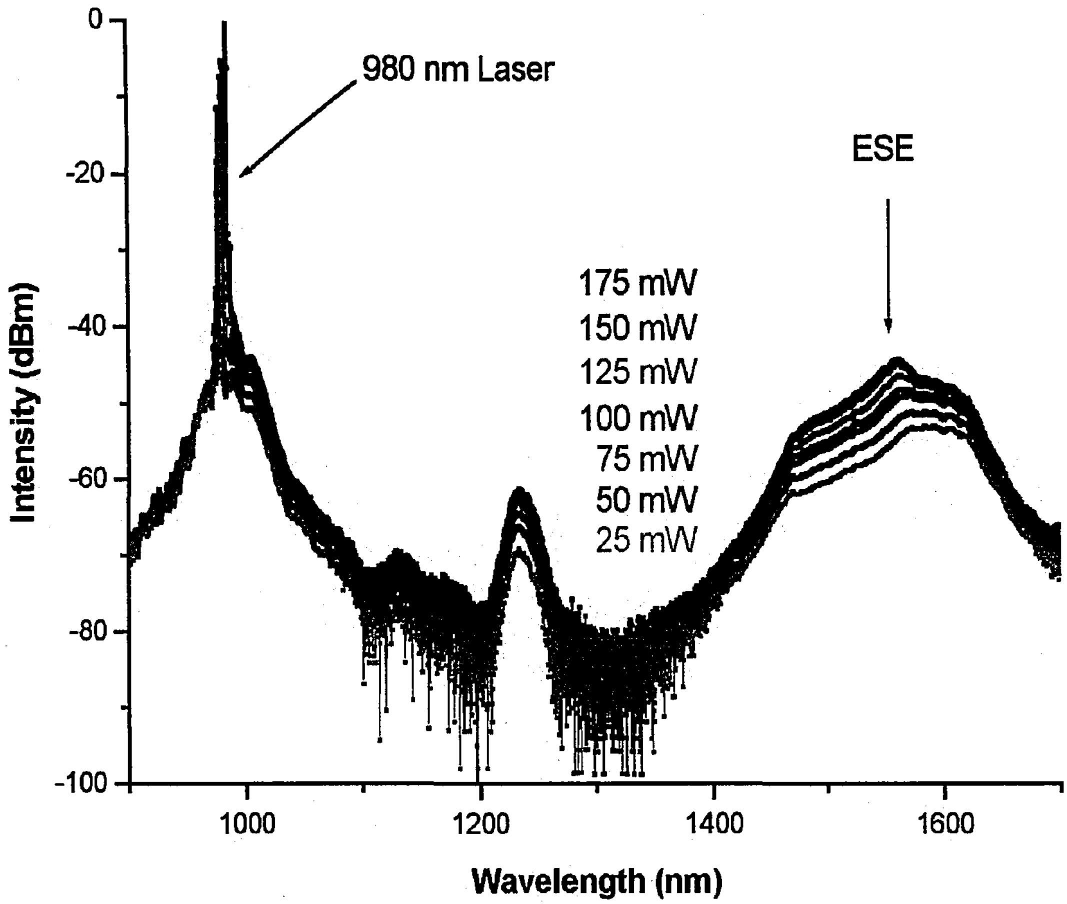
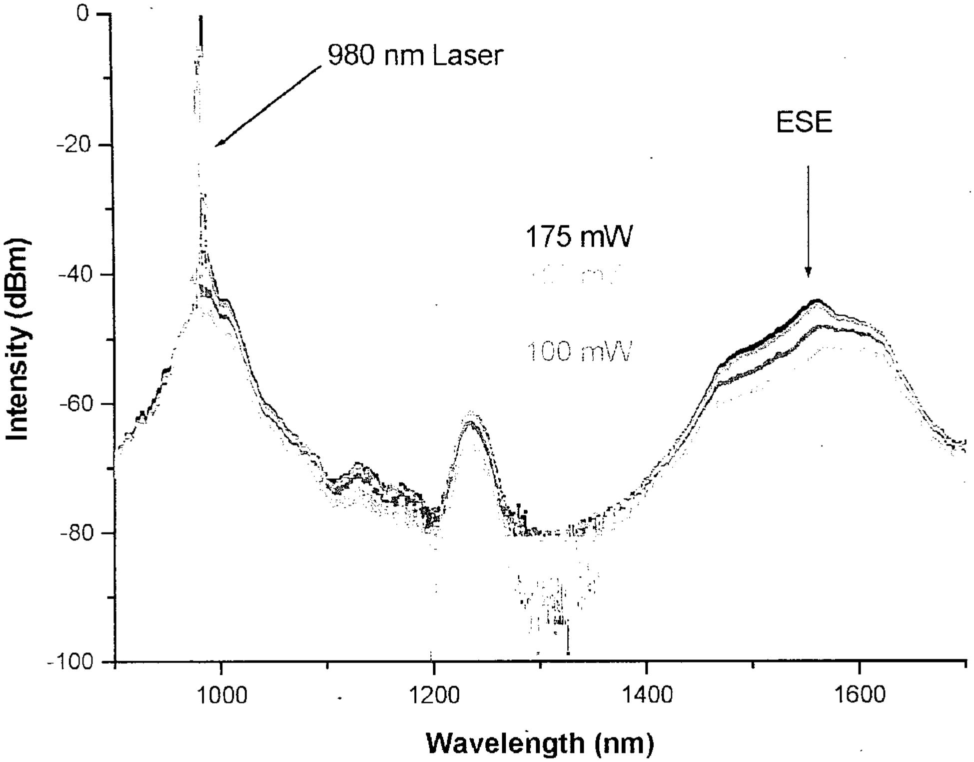


Figure 8 Transmission spectra of erbium doped telluride fiber (the length of the fiber is 100 mm).

Transmission spectra of erbium doped telluride are shown in Figure 8. I order to observe intensity dependence on input power, we measured spectra with 25, 50, 75, 100, 125, 150, and 175 mW of input power of 980 nm pump laser, respectively. As we can see, during the increasing of pump power, intensity of 980 nm line decreases as ESE increases, as expected. Intensity dependence on input power at 1560 nm is show on Figure 9.



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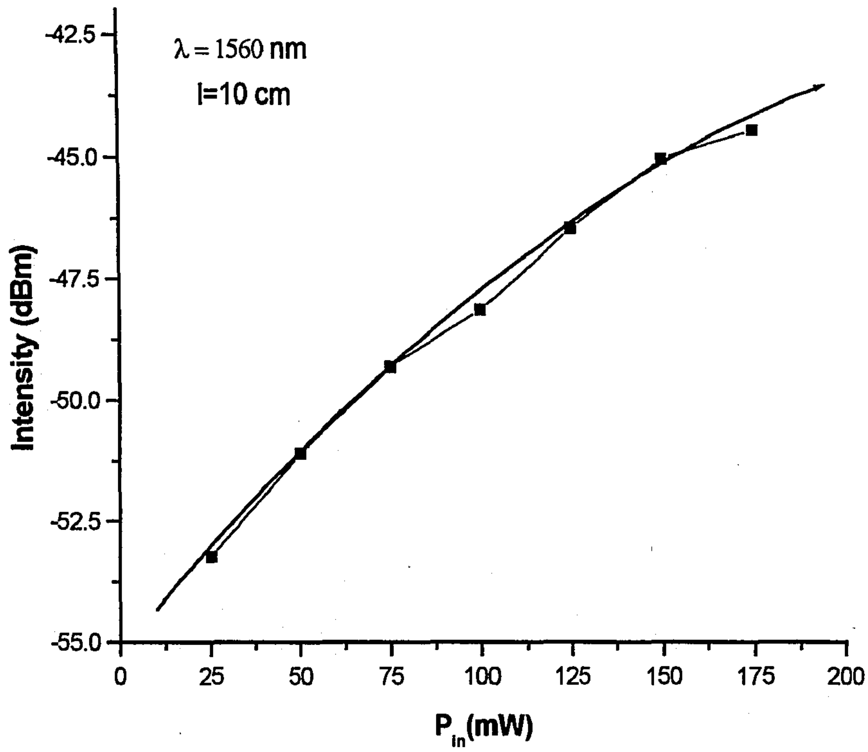


Figure 9 Intensity dependence on input power at $\lambda = 1560$ nm.

As expected, presented curve has tendency for saturation toward higher power. The concentration of erbium in the core of these fibers was 4000 ppm, which is very high. With such high concentration, and in longer samples, erbium can completely absorb pump light. Also, there is a limit in increasing the input power, because of overpopulation of erbium energy levels responsible for ESE.

Even with these relatively short samples, we were able to achieve some basic results like to see ESE, and to check for upconversion pumping processes, as well as to see the small signal behavior for 1560 nm laser. Certainly the most important achievement is very broad ESE, up to the 150 nm, which is shown on the Figure 9.

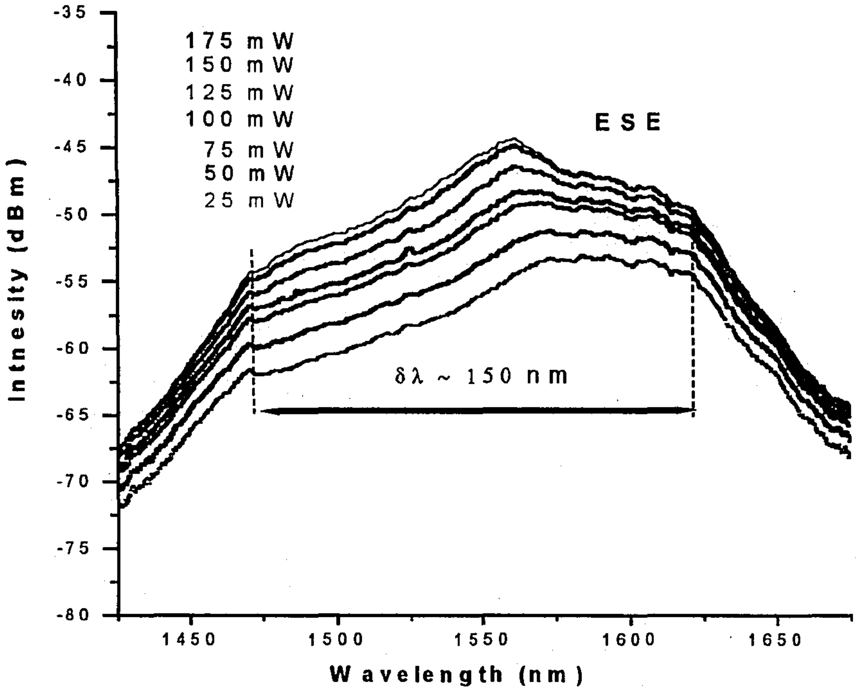


Figure 9 ESE in erbium doped telluride fiber.

The upconversion pumping presents itself as green light, which we can see in Figure 10. As we can see, the light shades away as it goes further from the part where we spliced silica fiber from the 980 nm pump. With 40 cm long sample, and with maximum of 120 mW of 980 nm light, we were able to see that light went through only to the half of the sample.

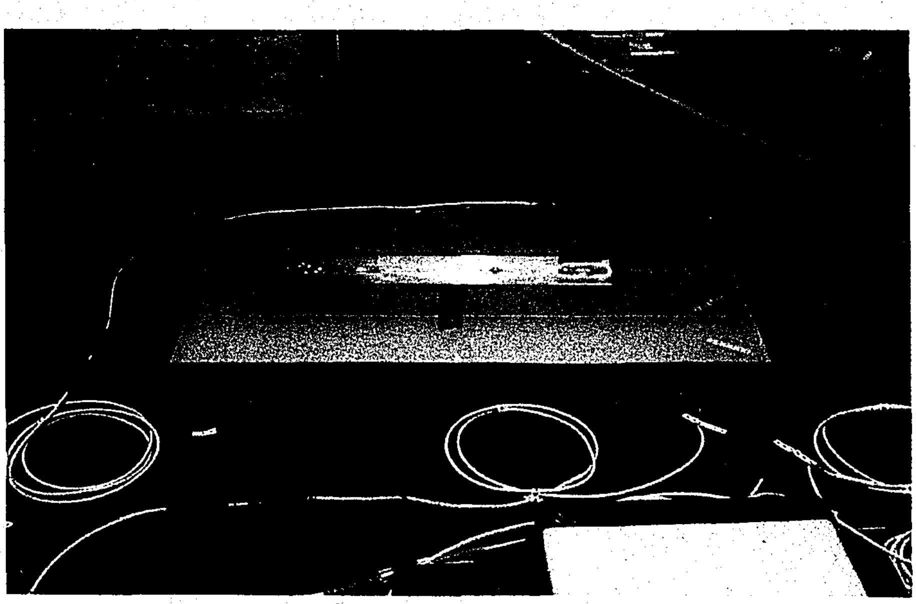
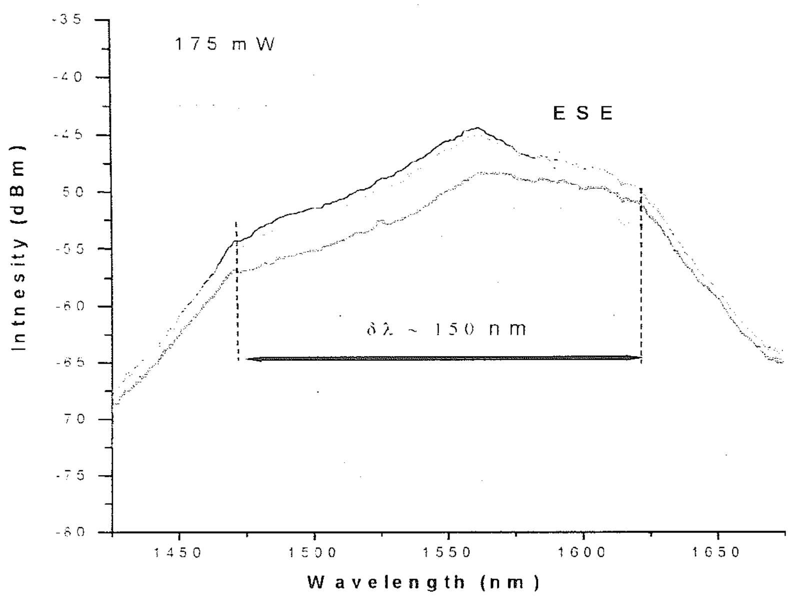


Figure 10 Upconversion pumping in the 125 mm long sample.



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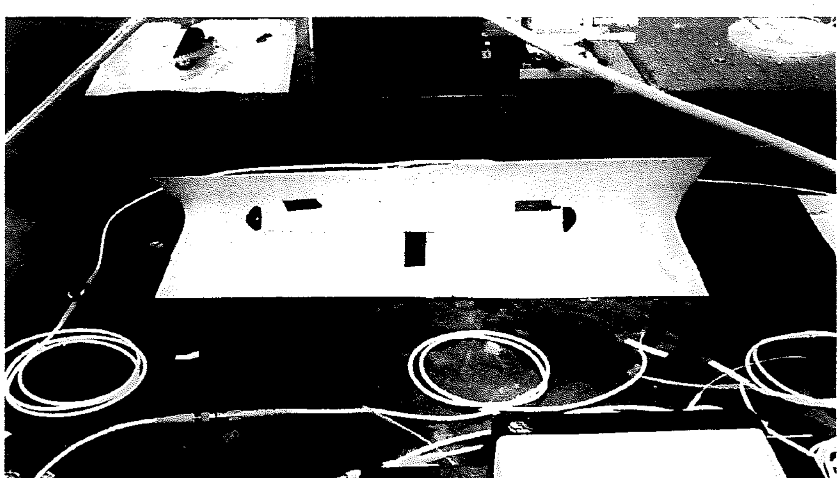

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There is no significant difference among transmission spectra of erbium doped telluride fibers with different lengths. We made samples with length of 7.5 cm, 10 cm, as well as 12.5 cm, and there are very similar, so we did not want to present them separately. The reason for this is that in order to get length dependence of transmission spectra, we need quite different lengths, like 10 cm, 20 cm, and 40 cm, for example. Also, these fibers we made are too short to show their full purpose - to amplify the signal with the total gain of 35 dB or 5 dB/mW of absorbed power. We have made some samples like 40 cm of length, but for those we need more powerful 980 nm pump, and a WDM coupler with very low loss.

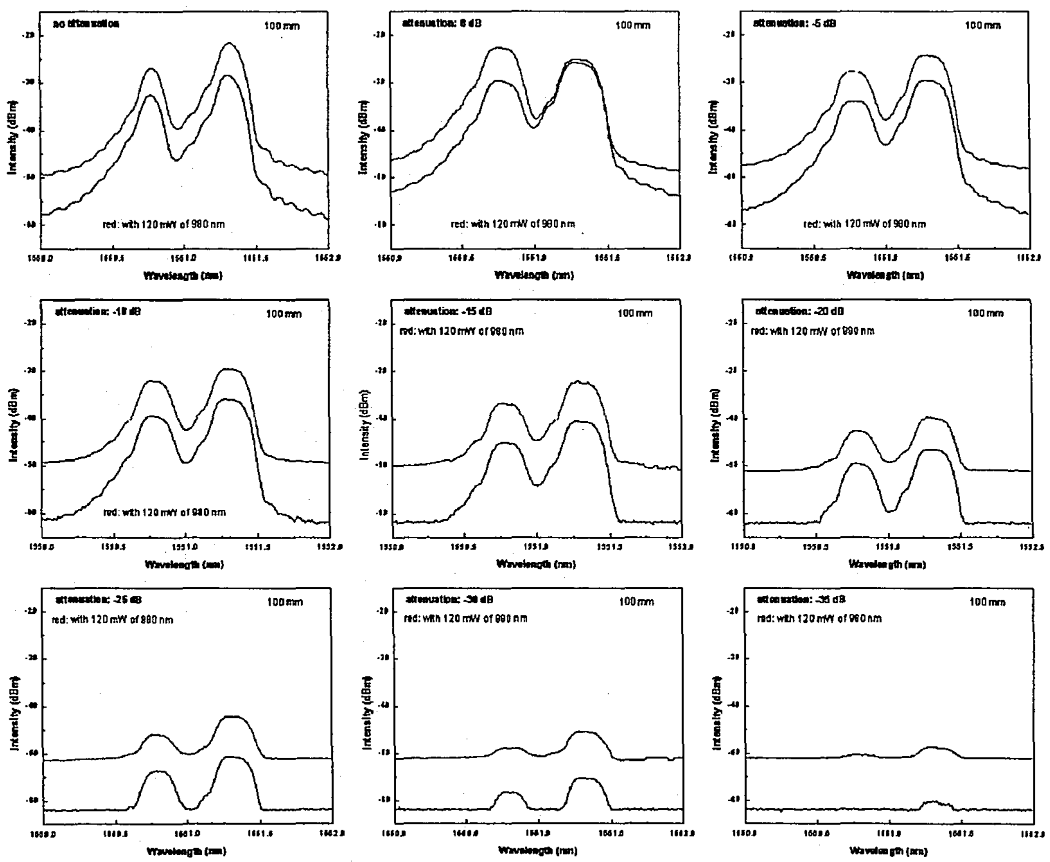

Figure 11 The 1550 nm line in the range from no attenuation to - 35 dB of attenuation (100 mm sample).

Finally, we have looked at low signal gain of 1550 nm laser. We checked several different low signals of 1550 nm light, using the attenuator for 0, -5, -10, -15, -20, -25, -30, and

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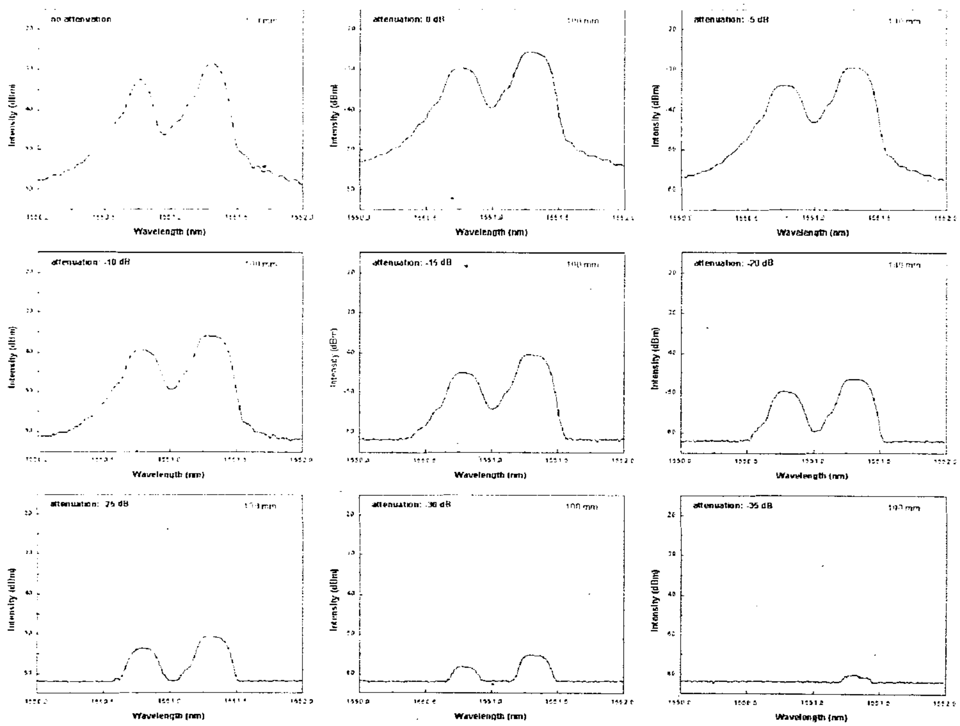

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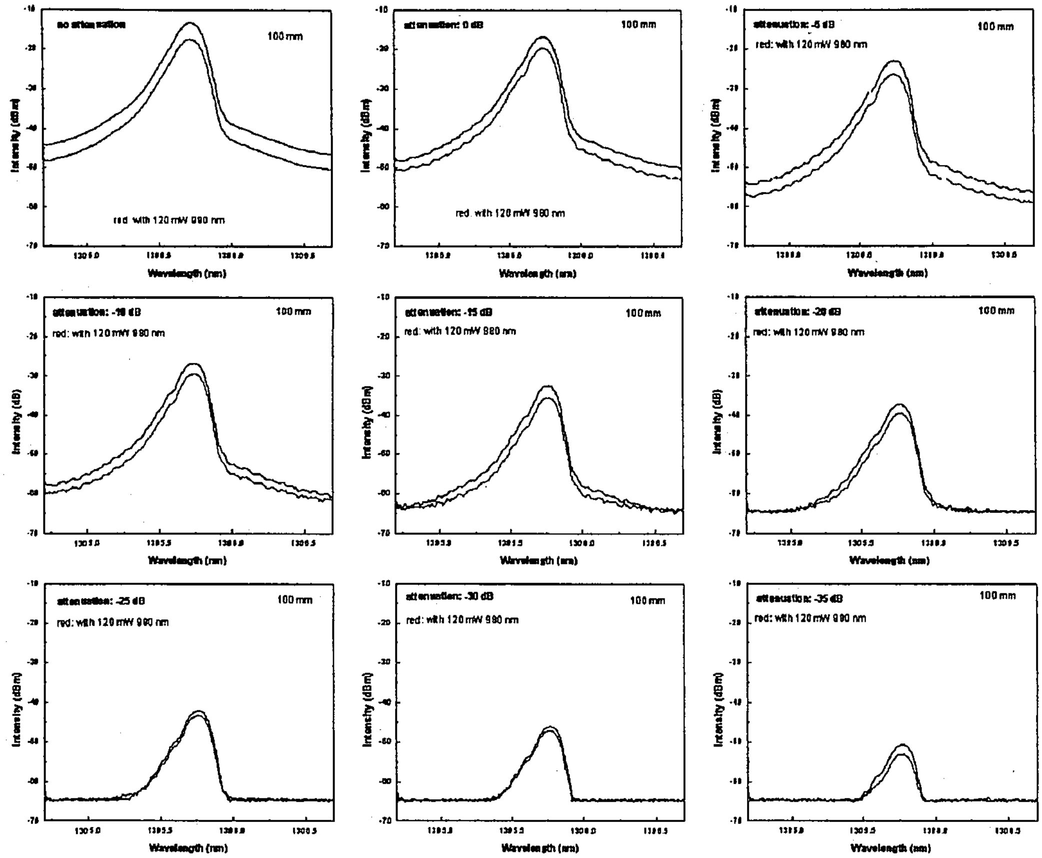

Figure 12 The 1300 nm line in the range from no attenuation to - 35 dB of attenuation (100 mm sample).

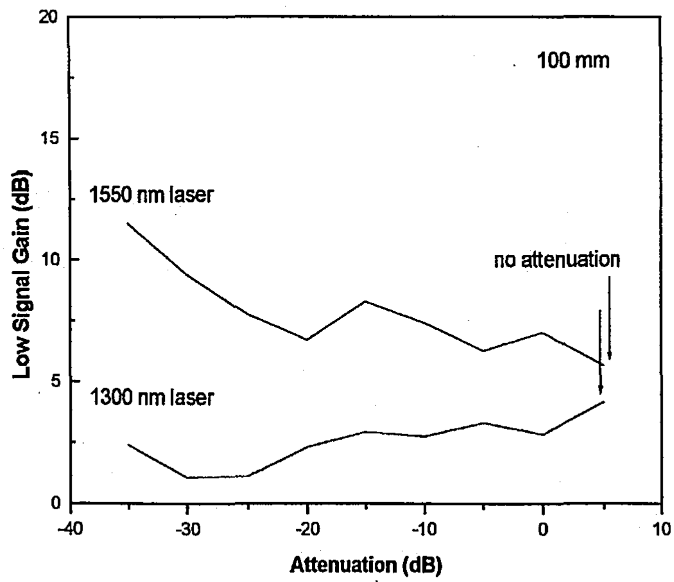

Figure 13. Low Signal Gain or on/off gain dependence on attenuation (100 mm sample).

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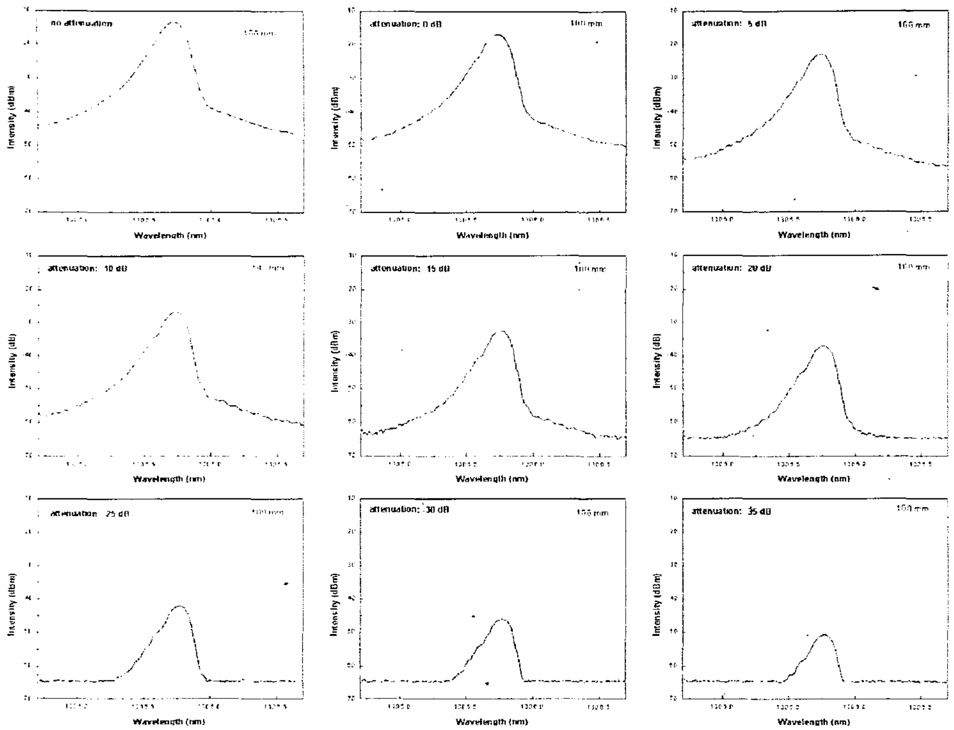

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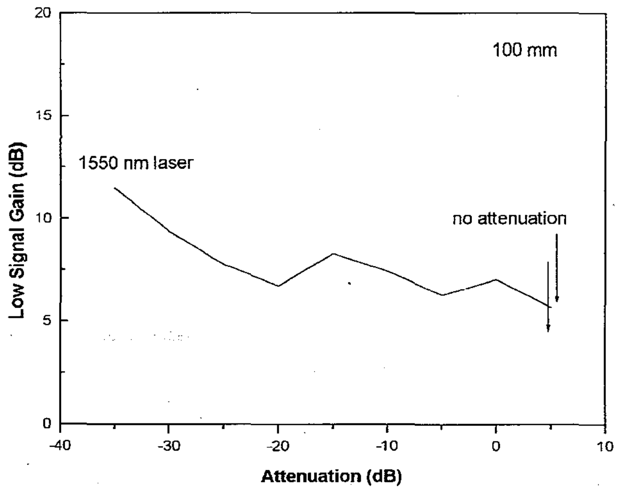

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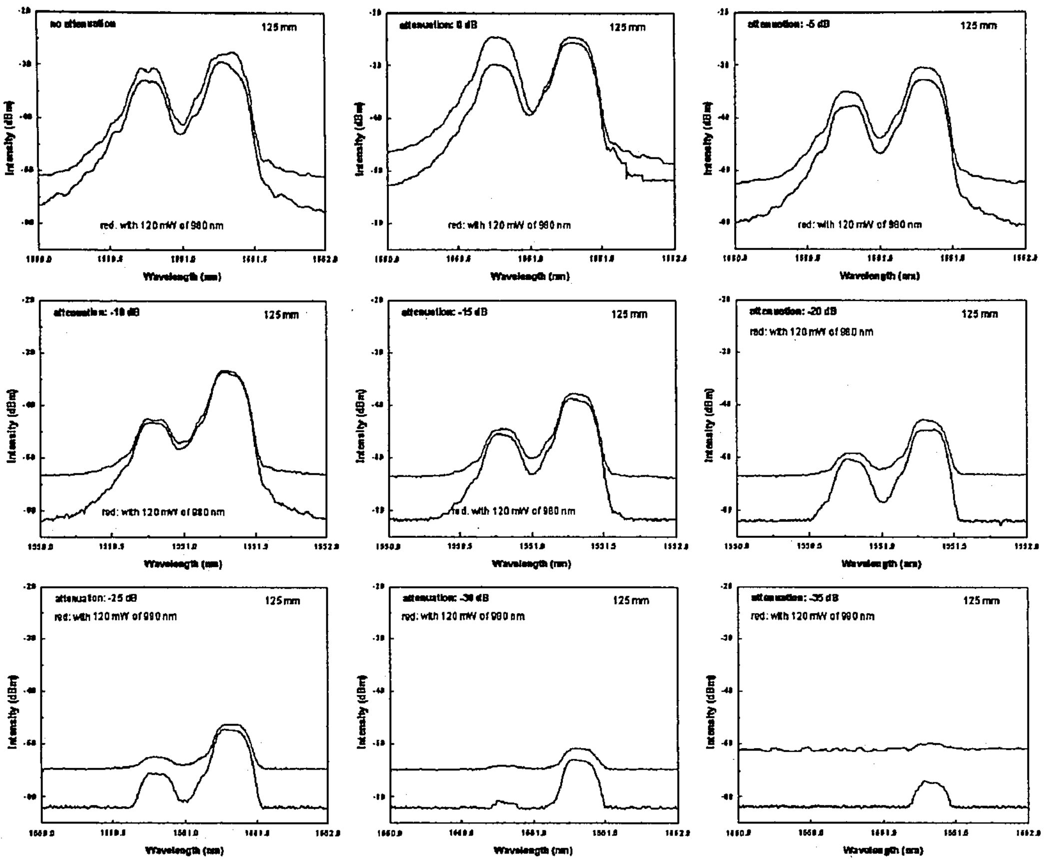
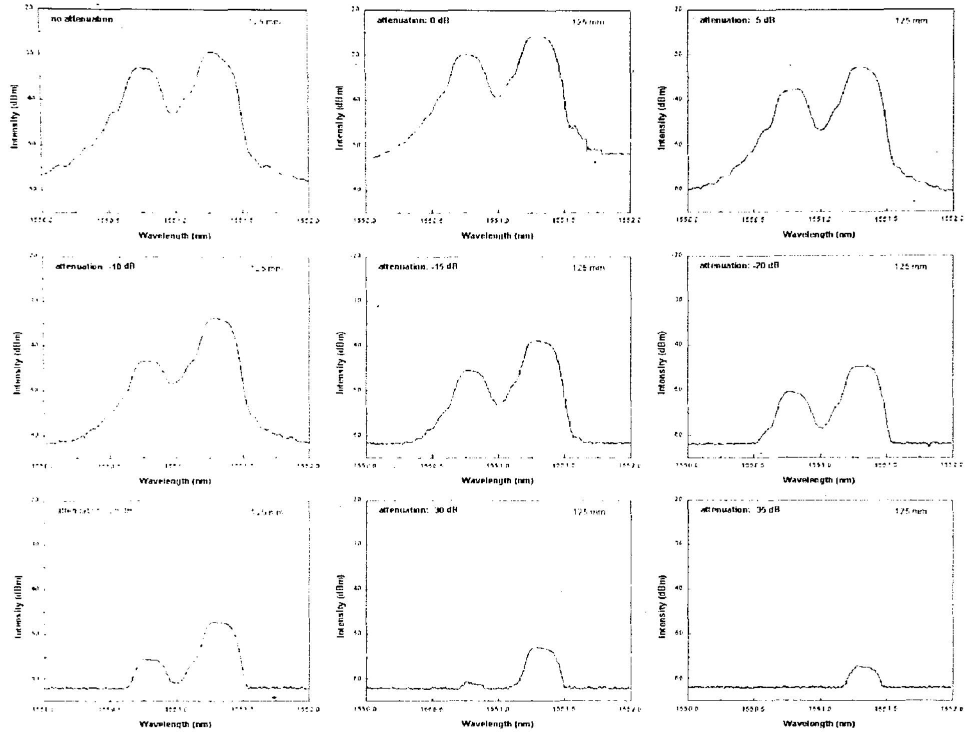


Figure 13 The 1550 nm line in the range from no attenuation to - 35 dB of attenuation (125 mm sample).

Very interesting result we received for the 1300 nm line in the sample of 100 mm. We did not expect to see any significant change of intensity of 1300 nm line, when we apply 980 nm lights from the pump. But, there is slightly decreasing of intensity. Low Signal Gain or on/off gain dependence on attenuation for 125 mm sample is similar to one for 100 mm, so we didn't want to present it separately.

Also, the low signal gain or, maybe better, on/off gain for sample with length of 100 mm was higher, approximately 6 dB, than the same signal gain in the sample with length of 125 mm. The reason for this is probably in the higher loss at the mechanically spliced parts in the sample with 125 mm of length.



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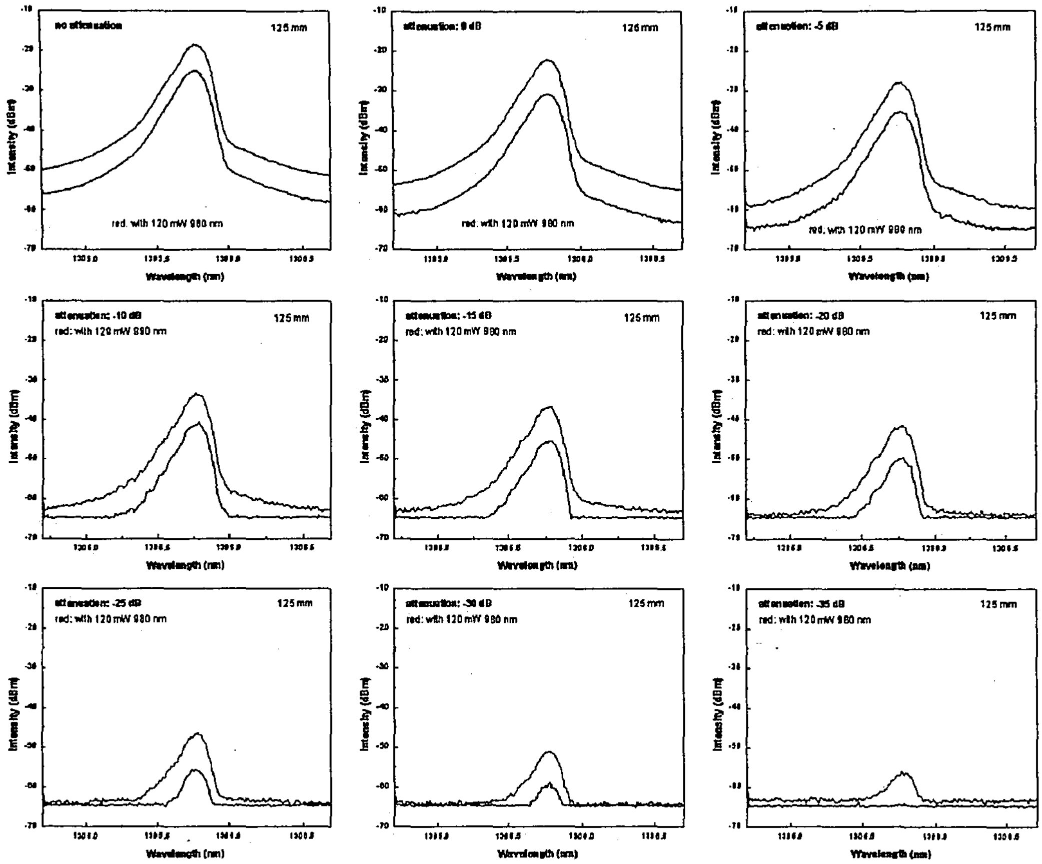

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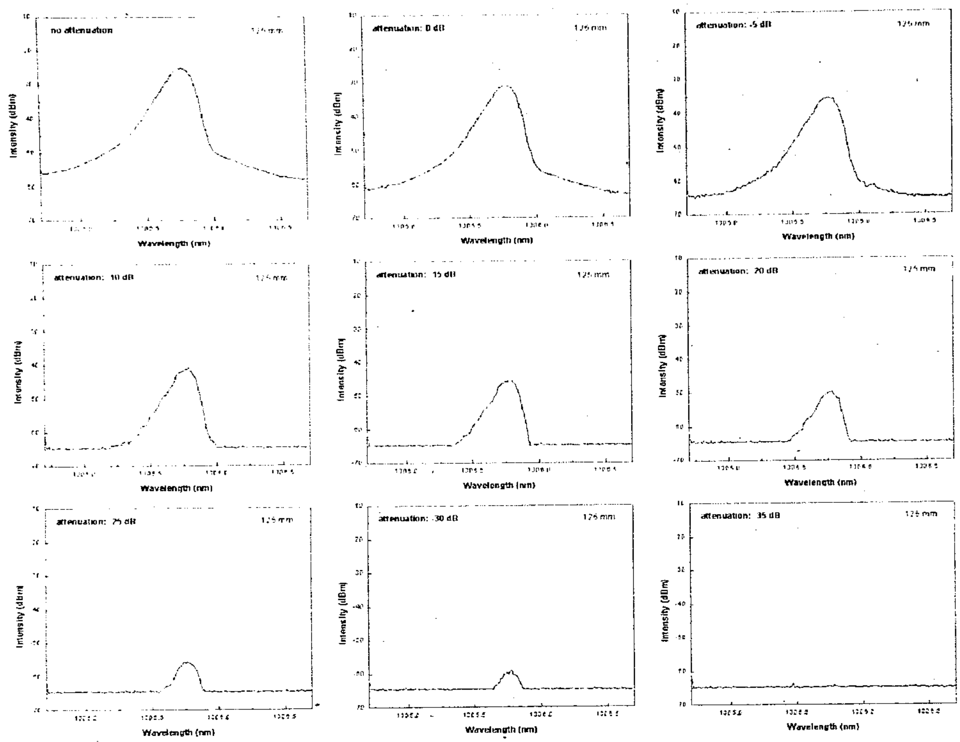

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Conclusion

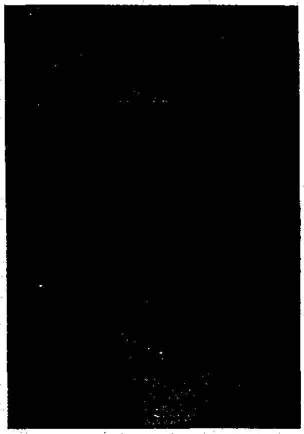
We measured the transmission of light through erbium doped TeO_2 fibers. We were using standard single mode 980 nm laser as a pump source. There is no significant difference among transmission spectra of erbium doped telluride fibers with different lengths we made. The up-conversion presents itself as green light and it shades away as it goes further from the part where we spliced silica fiber from the WDM. Also, we measure low signal gain or on/off gain dependence on attenuation.

Our further research should be pointed into improvement of the mechanical splicing, making longer amplifiers with higher amplification, and supplying more power from the 980 nm pump. These fibers can be used for different purpose, like highly efficient amplifiers or even lasers.

Literature

[1] Sudo, Shoichi (ed.), *Optical Fiber Amplifiers - Materials, Devices, and Applications*, Artech House, Inc., 1997.
[2] Quimby, R. S., W. J. Miniscalco, and B. Thompson, "Excited State Absorption at 980 nm in Erbium Doped Glass, " *Fiber Laser Sources and Amplifiers*, Vol. 1581,: SPIE, 1991, pp. 72-79.
[3] Quimby, R.S., "Output Saturation in a 980-nm Pumped Erbium-Doped Fiber Amplifier," *Appl. Optics*, Vol. 30, June 1991, pp. 2546-2552.
[4] Quimby, R. S., W. J. Miniscalco, and B. Thompson, "Excited State Absorption at 980 nm in Erbium Doped Silica Glass," *Tech. Digest of OAA '92*, Vol. 17, June 1992, pp. 67-70.
[5] Quimby, R. S., W. J. Miniscalco, and B. Thompson, "Upconversion and 980-nm Excited-State Absorption in Erbium-Doped Glass," *Fiber Laser Sources and Amplifiers*, Vol. 1789, : SPIE, 1992, pp. 50-57.
[6] Ainslie, B. J., S. P. Craig-Ryan, S. T. Davey, J. R. Armitage, C. G. Atkins, and R. Wyatt, "Optical Analysis of Erbium Doped Fibers for Efficient Lasers and Amplifiers," *Tech. Digest of IOOC '89*, Vol. 3, July 1989, pp. 22-23.
[7] Blixta, P., J. Nilsson, T. Carlnäs, and B. Jaskorzynska, "Amplification Reduction in Fiber Amplifiers Due to Up-Conversion at Er^{3+}-Concentrations Below 1000 ppm," *Tech. Digest of OAA '91*, July 1991, pp. 52-55.
[8] Sceats, M. G., P. A. Krug, G. R. Atkins, S. C. Guy, and S. B. Poole, "Non-Linear Excited State Absorption in Er^{3+}-Doped Fiber with High-Power 980 nm Pumping," *Tech. Digest of OAA '91*, Vol. 13, July 1991, pp. 48-51
[9] Krug, P. A., M. G. Sceats, G. R. Atkins, S. C. Guy, and S. B. Poole, "Intermediate Excited-State Absorption in Erbium-Doped Fiber Strongly Pumped at 980 nm," *Optica Lett.*, Vol. 16, Dec. 1991, pp. 1976-1978.
[10] Jau-Sheng Wang, Ph.D. Thesis, Rutgers University (1996).

Short Biography



I was born on September 9^{th} 1969, in Jagodina, a small city in the heart of my home country Yugoslavia. By the time I enrolled in high school it was already quite definite that physics was to be a lifelong challenge for me. My military service interfered with my studies at Belgrade University. I attended the Military Air Force Technical Junior College in Rajlovac, Sarajevo, B&H. I graduated with honors and as the best student in my class, on September 15^{th}, 1989, in the Group for Electronic Equipment of Aircraft, but most importantly, I "graduated" in working under extremely difficult conditions, and thus learned a lesson for life.

After that I was free to dive into my favorite subject - this of course being physics, and continue my education at Belgrade University - Faculty of Physics, where I attended lectures since September 1989, only to grow more and more certain that research in physics is the principal determining goal in my life! Since the 4th year of my undergraduate studies (since March 18^{th}, 1994, to be precise) I have been employed at the Institute of Physics in Belgrade, as an associate researcher. The research for my B.Sc. thesis: "Soft mode in $SrTiO_3$" was realized in the laboratories of the Institute of Physics in Belgrade, and represented a significant step toward solving some problems in physics. I graduated at Department of Physics of Belgrade University on July 13^{th}, 1995.

In February 1999, I accepted an offer from Lehigh University for PhD. Studies in physics. That was a real turnover of my life, and my carrier as well, since I finally could start my work in the area that I wanted for a long time - fiber optics. This thesis is just my first step toward my main intention - ever since I was a child my ultimate goal had been to become an independent researcher and soldier of science in some field of modern physics. I have chosen that to be fiber optics.

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END

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